South-West Electric Distribution Exchange (SWEDE) Conference
11-13 April 2022

On the Moon to Stay

Challenges Presented to Power Distribution by Sustained Operations on the Lunar Surface

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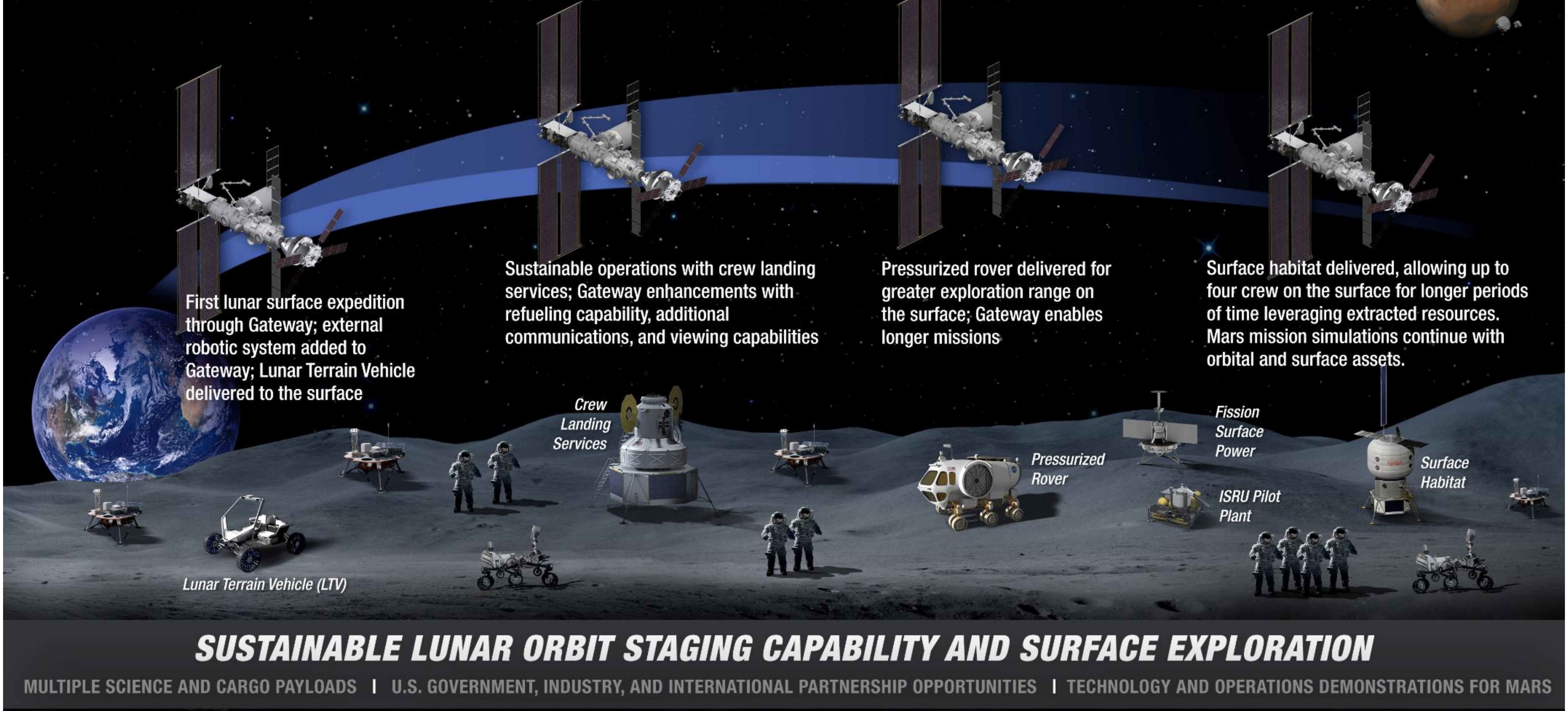
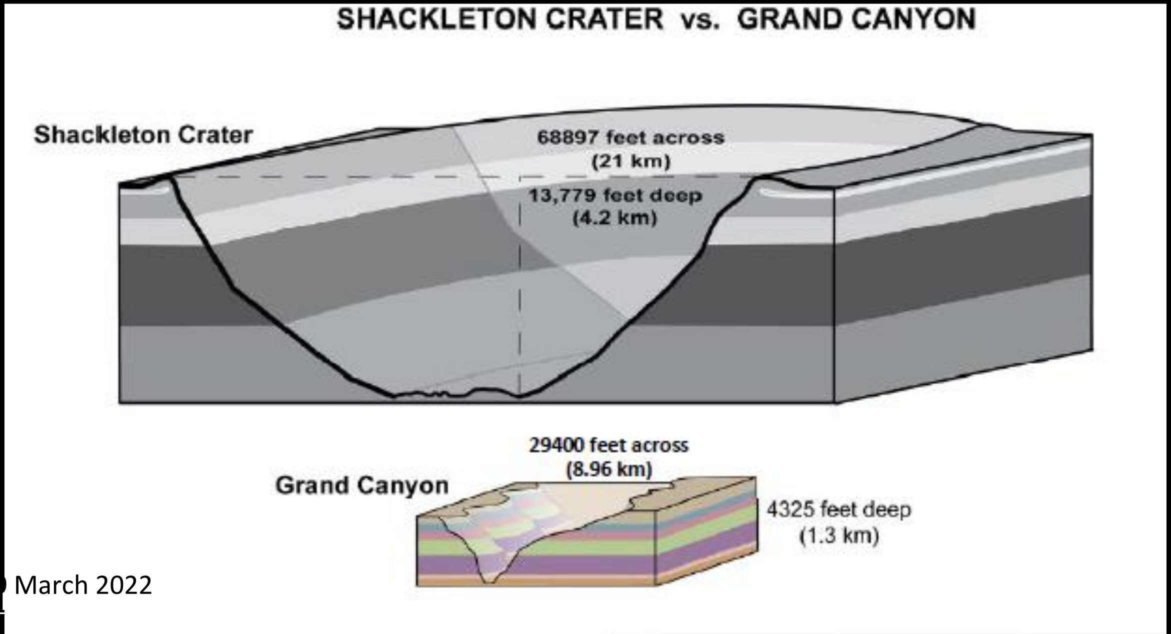
30 March 2022

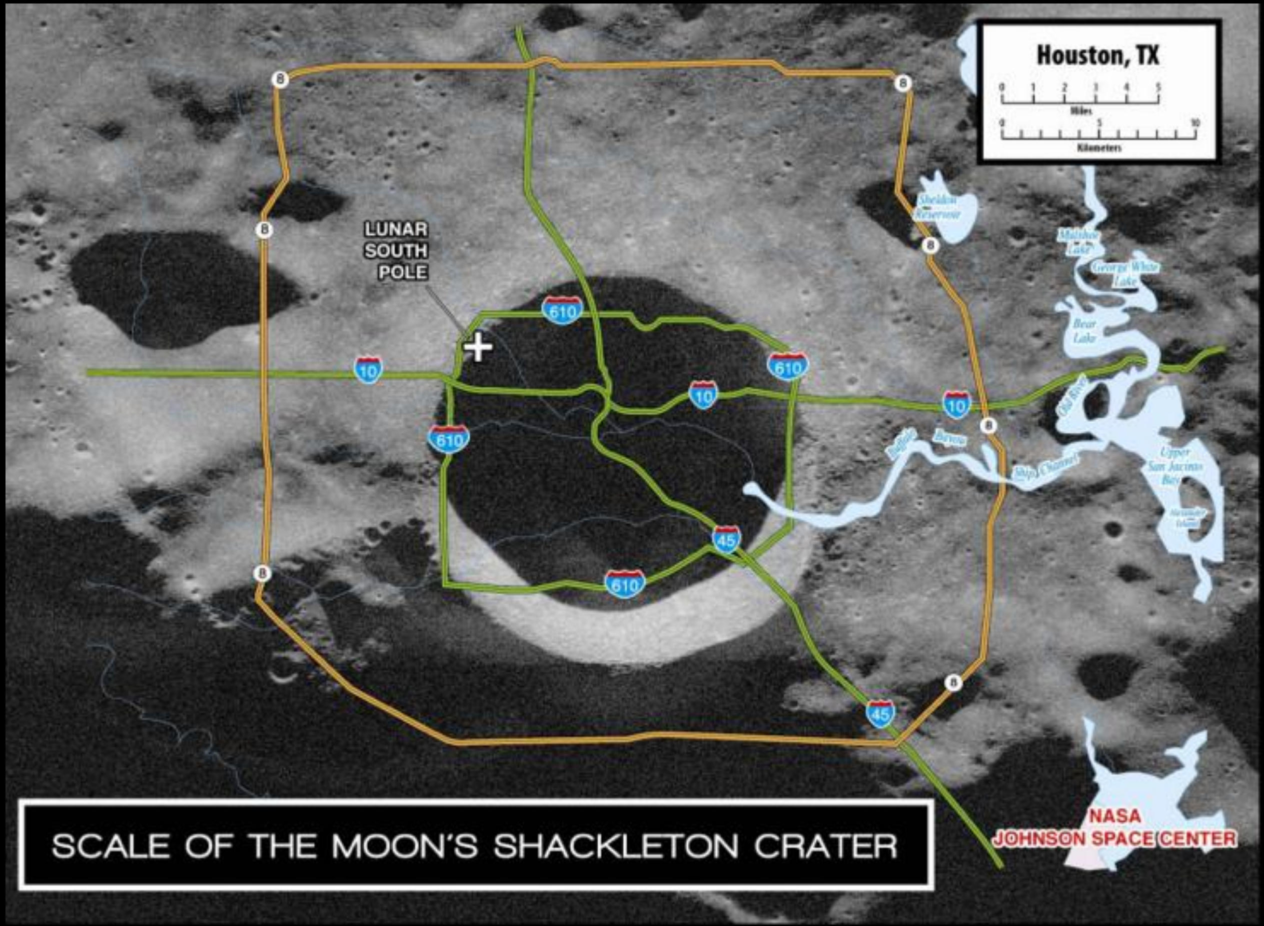
Artemis Base Camp Buildup



Shackleton Crater

- ~20 km in diameter
- ~4 km deep and ~3x deeper and wider than the Grand Canyon at Enfilade Point
- Located at Lunar South Pole
- Rim and Connecting Ridge are primary targets for future lunar landings





Artemis Base Camp Zone

POWER

The key commodity needed to exploit the Lunar Surface

Equatorial Illumination Limits

- Cyclical periods of 14 days illuminated, 14 days dark
- Consistent

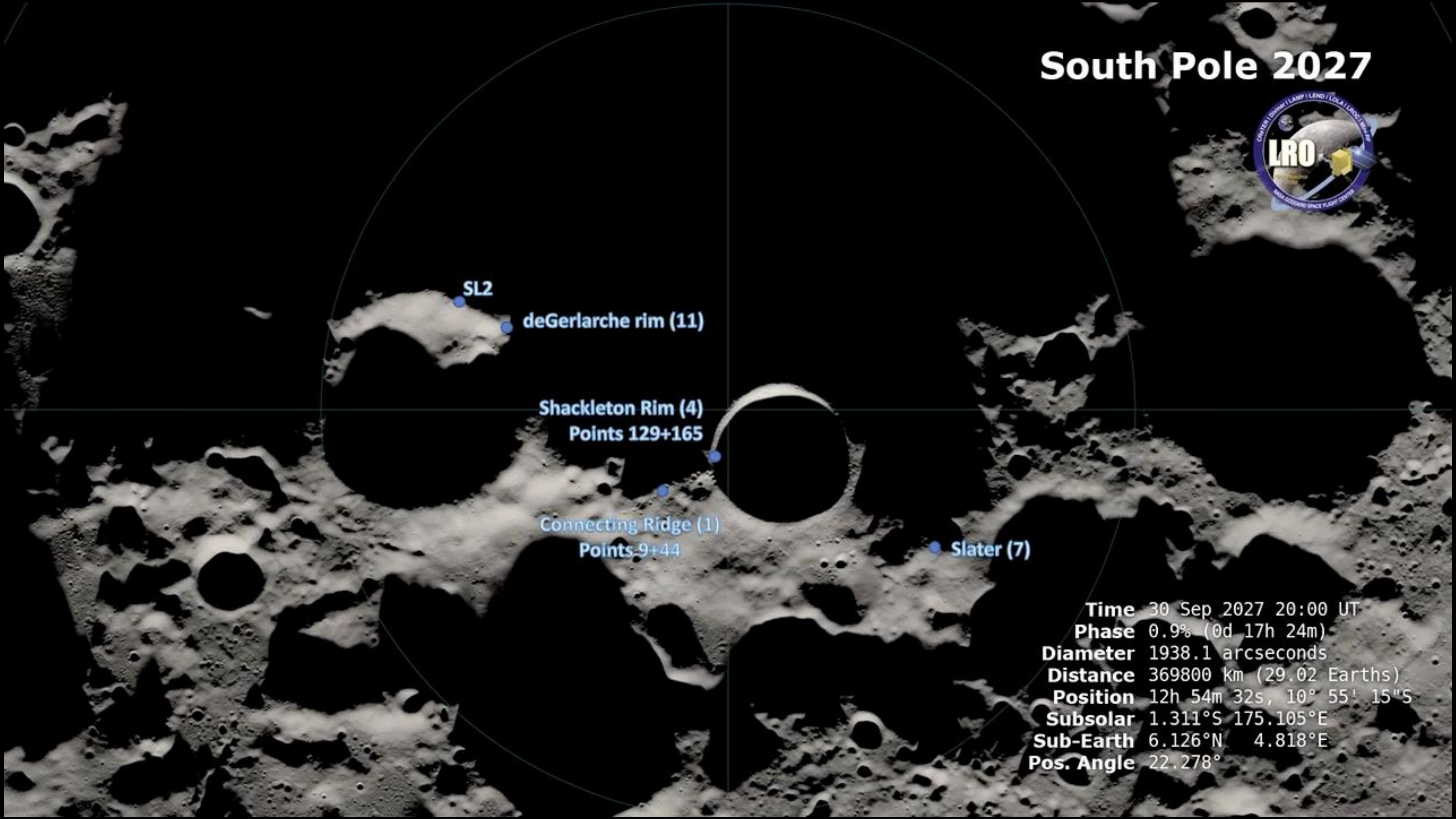
Illumination

The scarce resource needed to produce power

Polar Illumination Limits

- Intermittent with up to 100 hours darkness
- Highly dependent on location/elevation

90-Day Illumination Cycle at South Pole



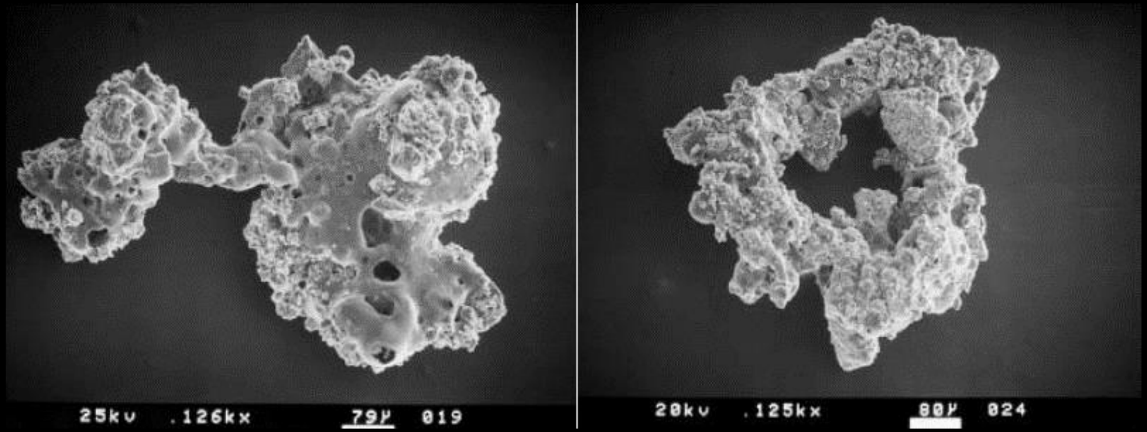
Lunar Surface Environment

Dust and Thermal Extremes are challenges in general.

Lunar Surface Temperatures

-173 C to 130 C
(-250 C in Permanently Shadowed Regions)

Lunar regolith (incl. lunar dust) is angular, abrasive, irregular in shape, small in particle size, and adheres to surfaces



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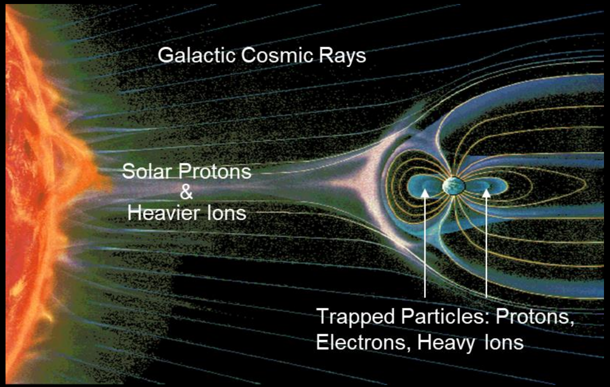
Lunar Surface Environment

RADIATION is the more difficult problem, particularly for semiconductors

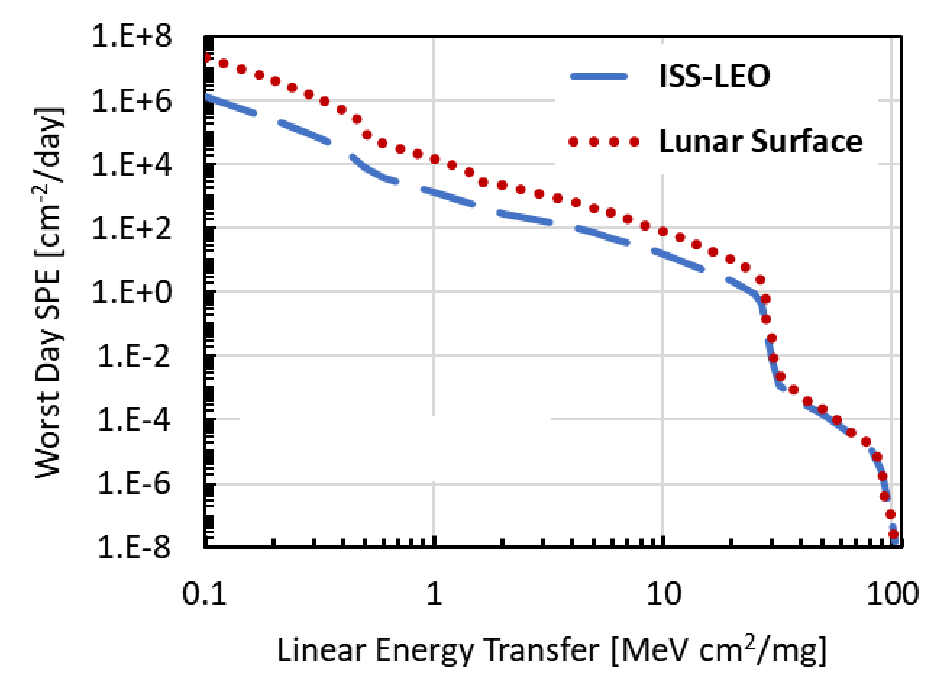
Total Ionizing Dose

Orbit	~1-year TID (2.5 mm Al) krad(Si)
Jovian	1000
GEO	150
Lunar Orbit	4
Lunar Surface	2
ISS LEO	2
Earth Surface	< 0.001



Single Event Effects

"Achilles' Heel" of Wide Band Gap Materials



SiC Diode

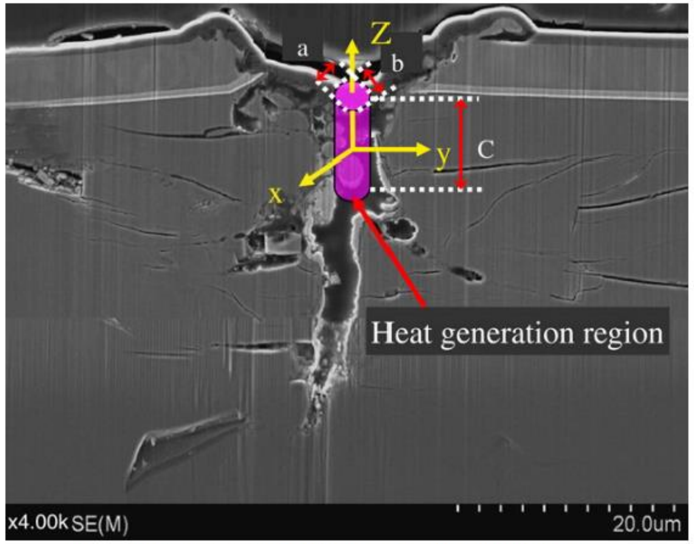


Image: Shoji, et al., © (2014) The Japan Society of Applied Physics, used with permission.

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Trade Space for Electric Power Grids

Terrestrial Utility Systems:

- Development, Installation, and Operation Cost ($/kW)
- Specific Power (kW_e/kg)
- Emissions (NO_x, CO_x, noise)

Constraint: Public Safety

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Trade Space for Electric Power Grids

Lunar Surface Utility Systems:

- Specific Power (kW_e/kg)
- Specific Power (kW_e/kg)
- Specific Power (kW_e/kg)
- Development Cost

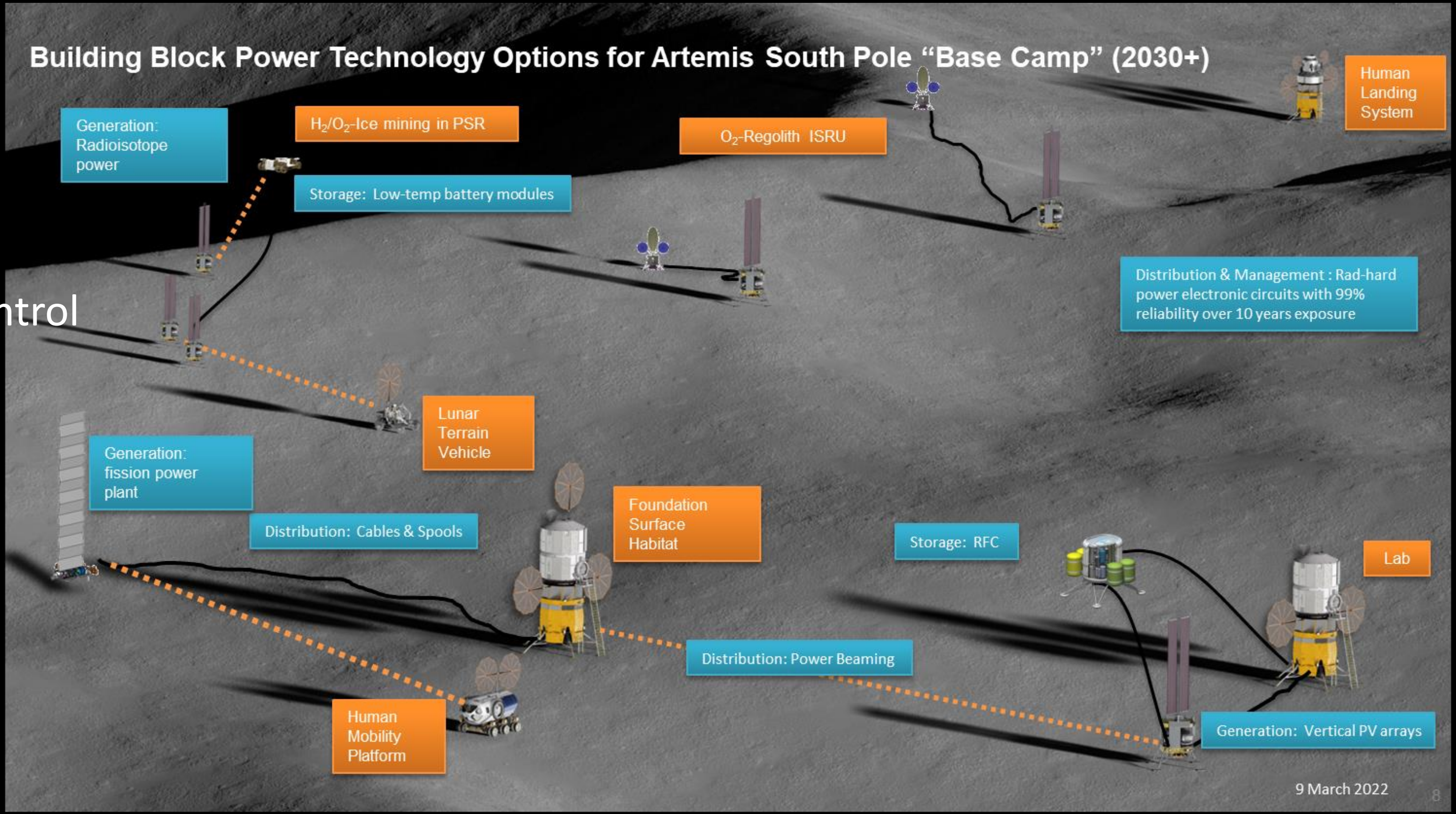
Constraint: Full Mission Reliability

Technology for Lunar Surface Power

NASA tasked to support the development of the intellectual property for the building block technologies from which industry will create the power infrastructure for the Lunar surface.

Building blocks include:

- Power Generation
- Energy Storage
- Power Management, Distribution, and Control



Contractual mechanisms range from government direct funding and government/industry partnerships for systems to SBIR contracts and research grants for basic component development

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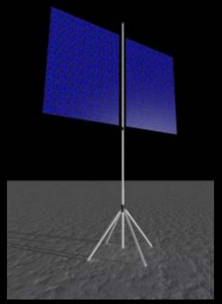
Technology for Lunar Surface Power

Power Generation

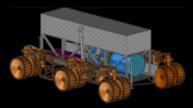
Photovoltaic Arrays:
Vertical Solar Array Technology (VSAT) Project
(NASA contract to industry)

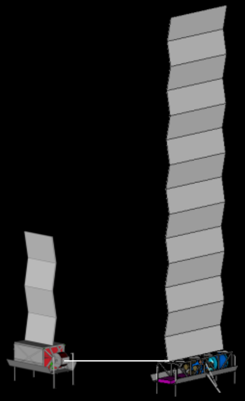
Potential Lunar Surface Demo
- 10 kW_e module
- 120 VDC output
- Vertical deployment mast ~10 m



Nuclear Fission:
Fission Surface Power (FSP) Project
(NASA/DoE contract to industry)

Planned Lunar Surface Demo
- 40 kW_e module
- Mobile/relocatable
- 240 VAC output rectified up to 3000 VDC

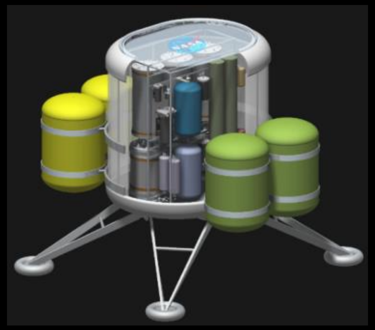




Grid-scale Energy Storage

Regenerative Fuel Cell:
Regenerative Fuel Cell (RFC) Project
(NASA in-house)

Potential Lunar or ISS Demo
- 100 W_e prototype module scalable to 7 kW_e
- 120 VDC output
- Up to 500 Wh/kg



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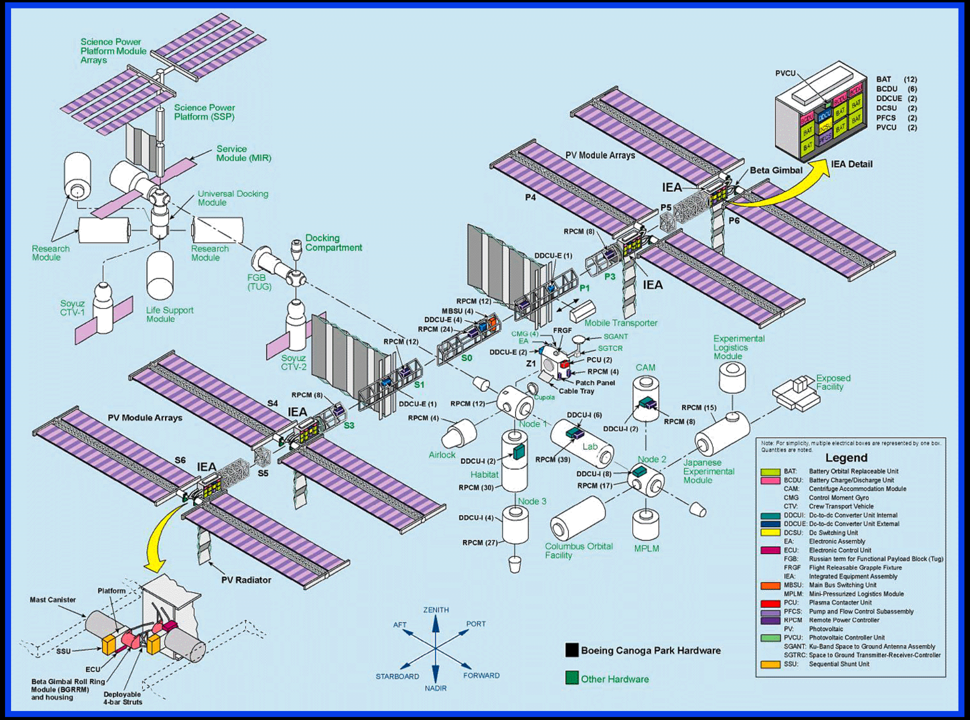
NASA's State-of-the-Art for Space Power Distribution: International Space Station and Gateway

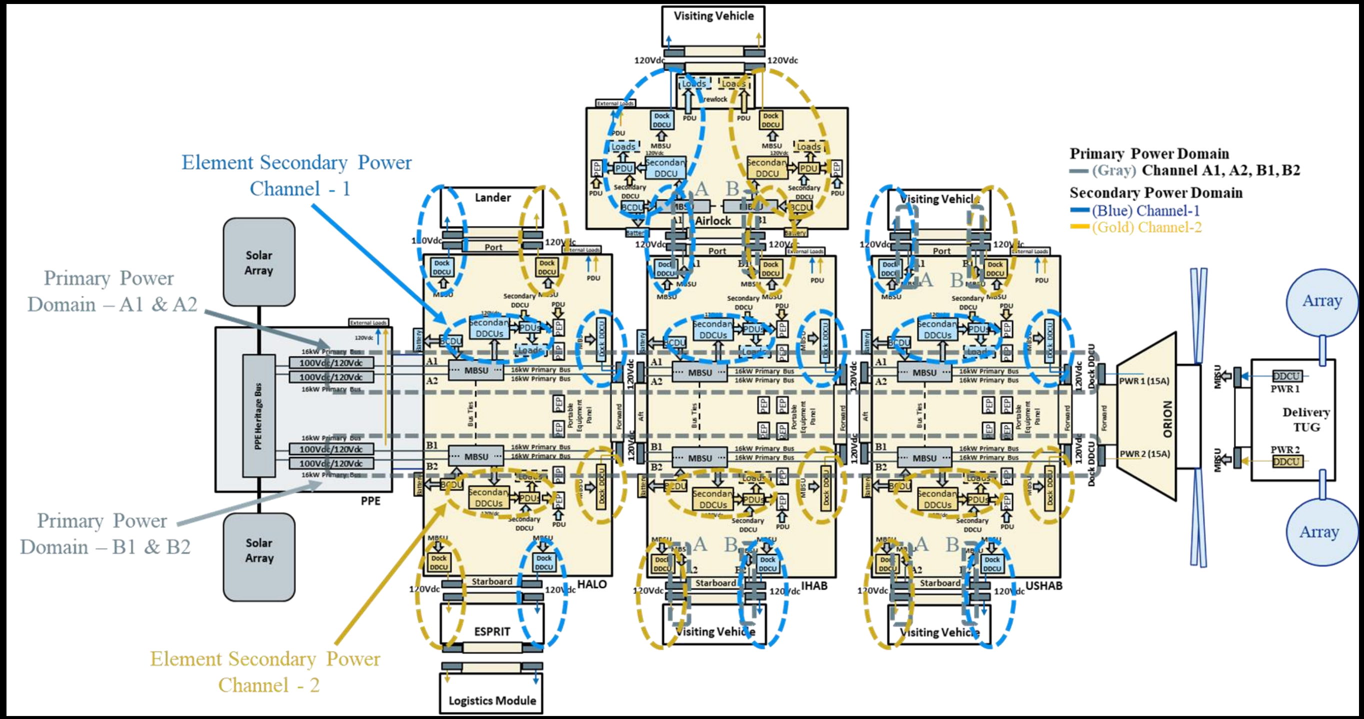
Photovoltaic generation with chemical battery storage
- 120 V regulated bus in ISS US segment and Gateway
- 28 V unregulated bus in ISS Russian segment

Standards define:
- Single point ground
- Two-wire (hot-return) cabling
- Isolation
- Source/load impedance separation, stability, voltage ripple, etc.

International Space Station
Standard: SSP 52051



Lunar Gateway
Standard: ISPSIS



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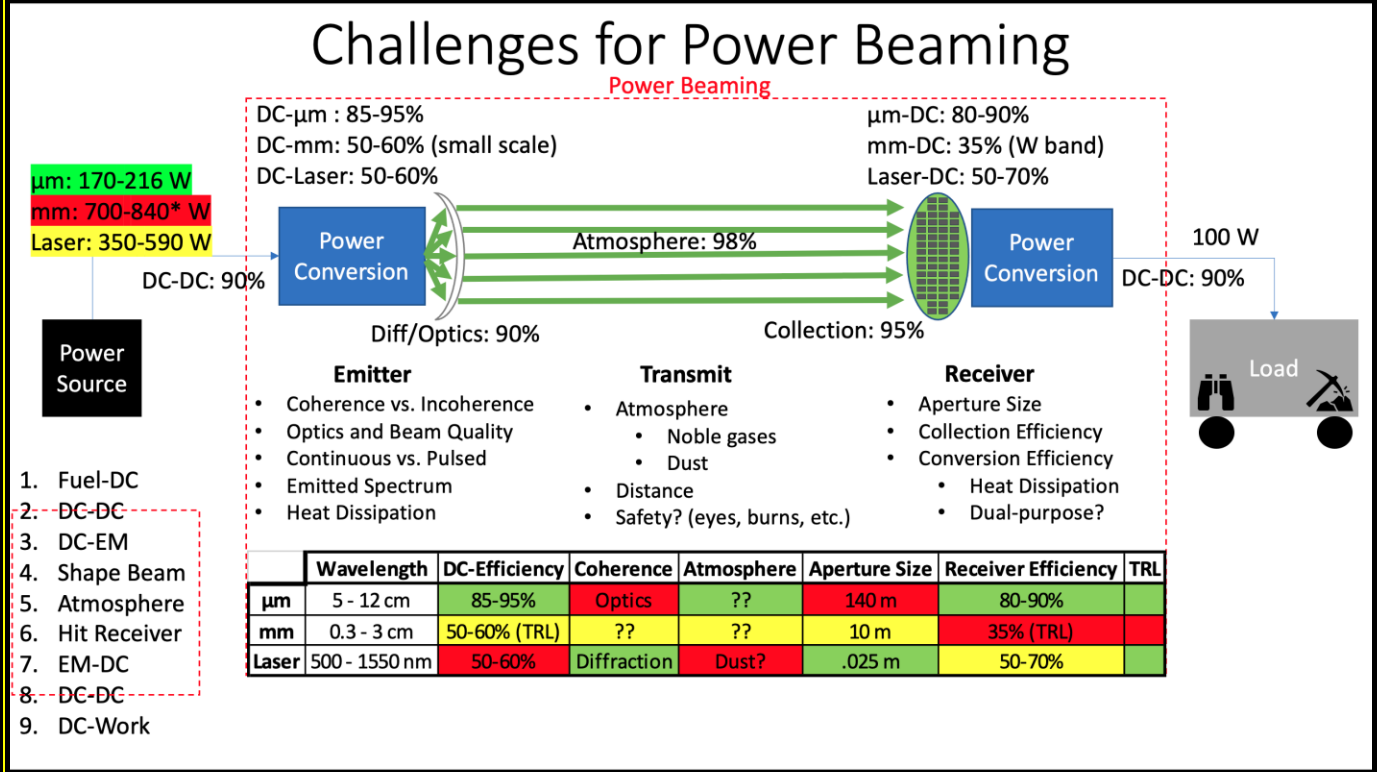
Technology for Lunar Surface Power

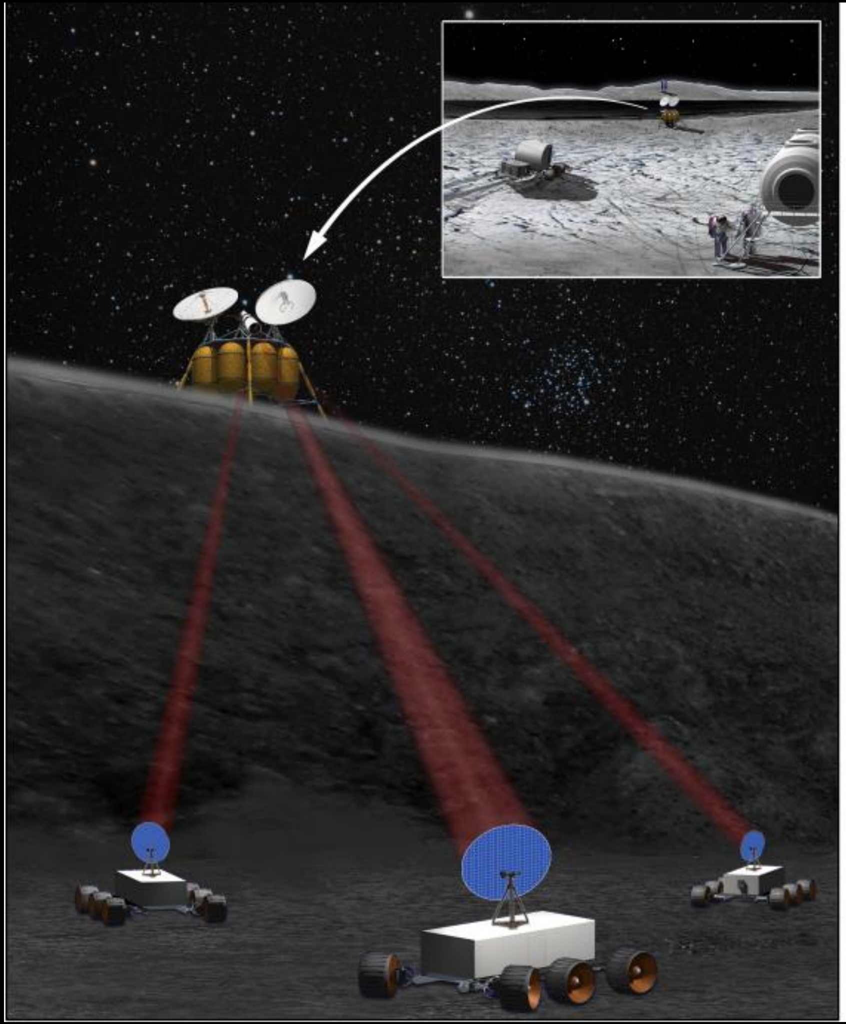
Power Management, Distribution, and Control

Wireless Transmission:
University of California at Santa Barbara
NASA grant (academia)

Lunar surface application: LASER transmission



	Wavelength	DC-Efficiency	Coherence	Atmosphere	Aperture Size	Receiver Efficiency	TRL
µm	5 - 12 cm	85-95%	Optics	??	140 m	80-90%	
mm	0.3 - 3 cm	50-60% (TRL)	??	??	10 m	35% (TRL)	
Laser	500 - 1550 nm	50-60%	Diffraction	Dust?	.025 m	50-70%	



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Technology for Lunar Surface Power – Current Projects

Power Management, Distribution, and Control *(cont'd)*

Radiation-Hardened Power Electronics

Tether Power Systems for Lunar Surface Mobility and Power Transmission (TYMPO)
NASA in-house

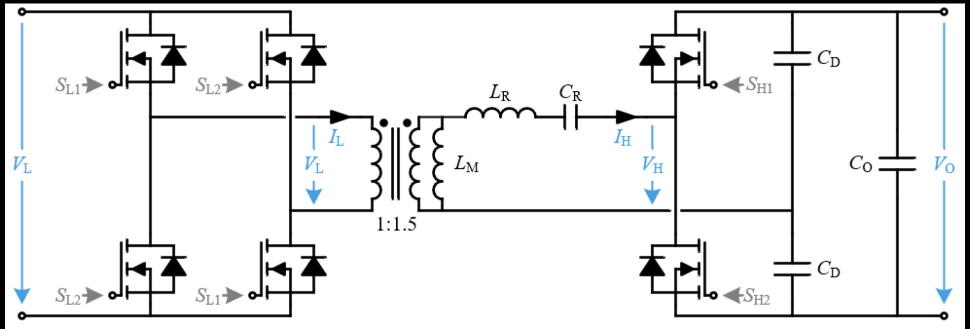
- Study includes GaN converter boost/buck between 100 VDC and 1500 VDC

Modeling, Testing, and Simulation of Heavy-Ion Basic Mechanisms in Si-C Power Devices
Vanderbilt University
NASA LuSTR grant (academia)

Various SBIRs/STTRs on materials

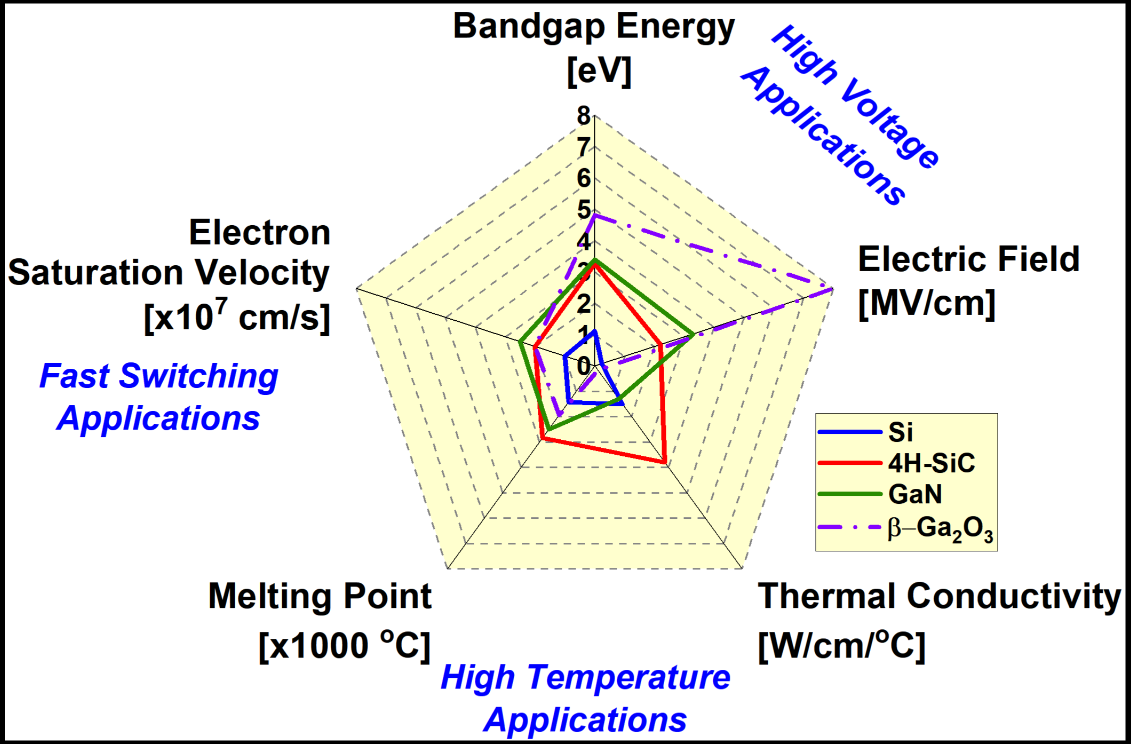
Typical Staged Boost Converter Module

Courtesy: JPL TYMPO



Semiconductor Performance Trades

Graphic: courtesy J.-M. Lauenstein, NASA/GSFC



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Power Management, Distribution, and Control *(cont'd)*

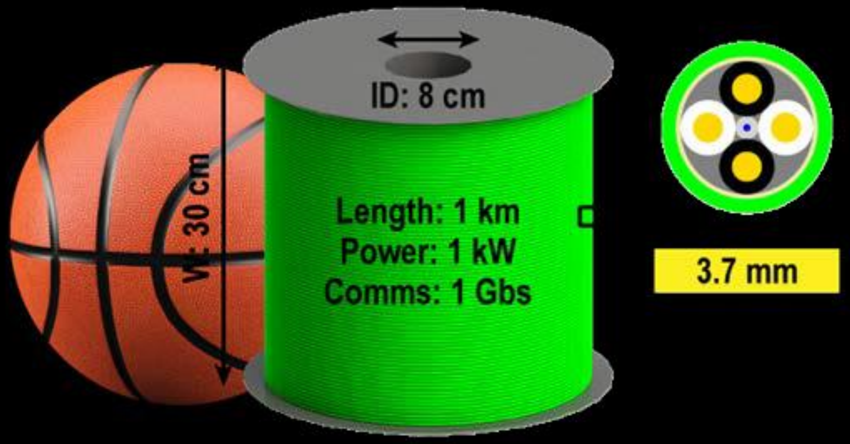
Cable and Spool:

Tether Power Systems for Lunar Surface Mobility and Power Transmission (TYMPO)

NASA in-house

Lunar and Planetary surface applications

- Study includes converter GaN boost/buck between 100 VDC and 1500 VDC
    - *3-ϕ AC cable w/neutral requires more conductors (heavier)*
- Up to 2 kW_e over up to 2 km for each cable
- 10 Mbs communication link
- Active Spool
- 4 X 22 AWG wire with Tefzel insulation



Technology for Lunar Surface Power – Current Projects

Power Management, Distribution, and Control *(cont'd)*

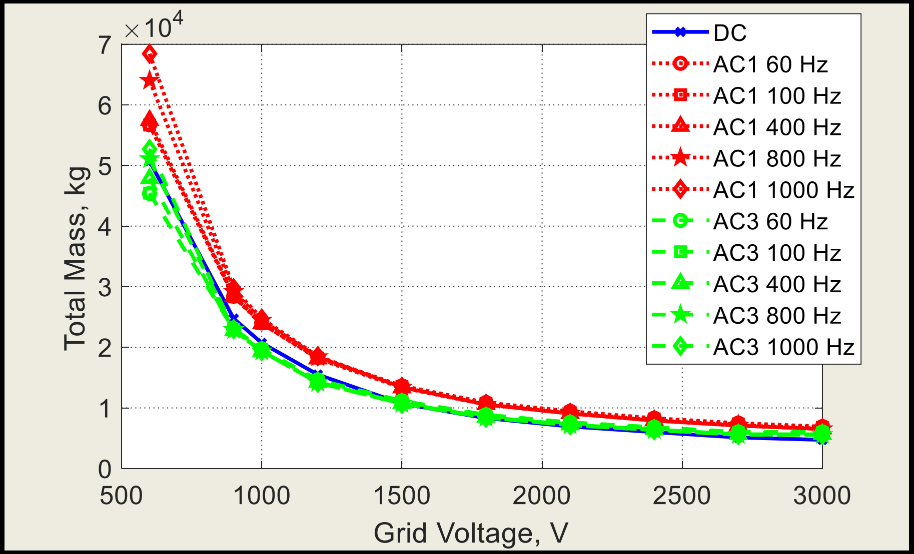
Boost/Buck Conversion for Transmission

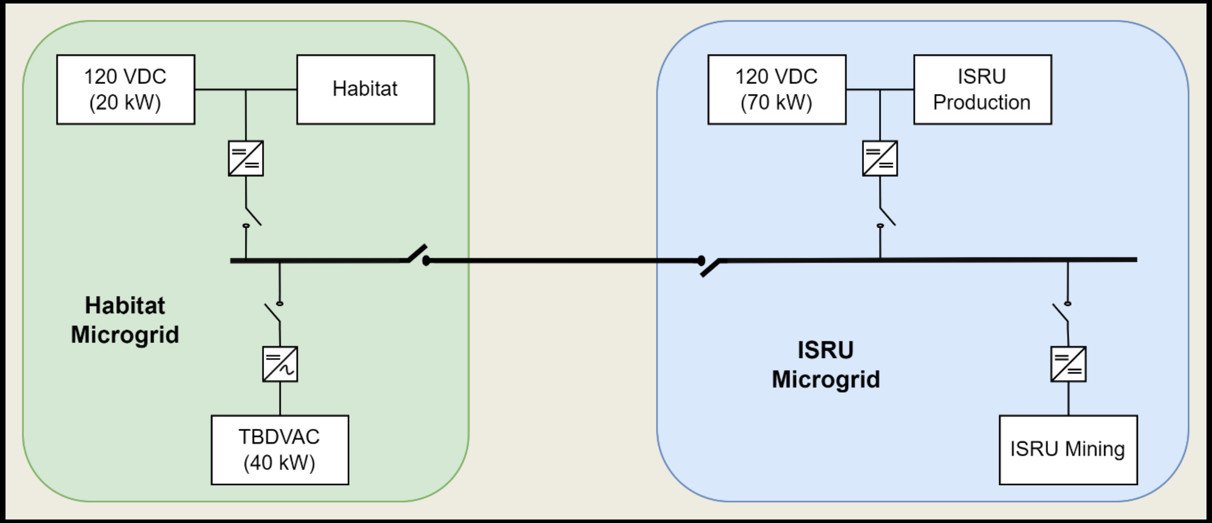
Micro-grid Definition and Interface Converter for Planetary Surfaces (MIPS)

NASA in-house

Developing prototype Universal Modular Interface Converter (UMIC)

- Boost/Buck between 120 VDC source/load at 1000 VDC transmission for standard power interface
- Assume radial architecture with up to ~1 km transmission of 10 kW





Note: initial trade on ~1 km transmission at 1000 V distance indicates that AC offers no advantage in system mass

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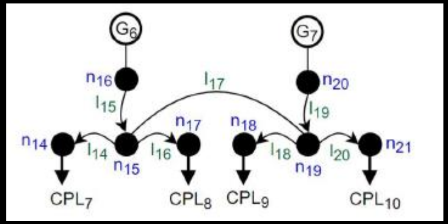
Power Management, Distribution, and Control *(cont'd)*

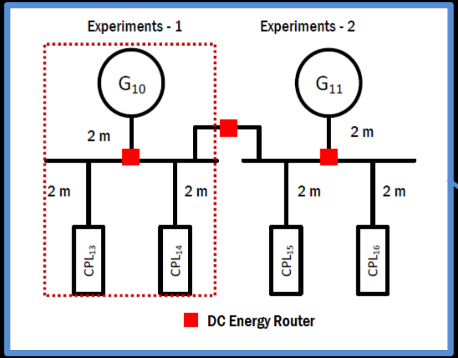
Voltage Regulator for Transmission

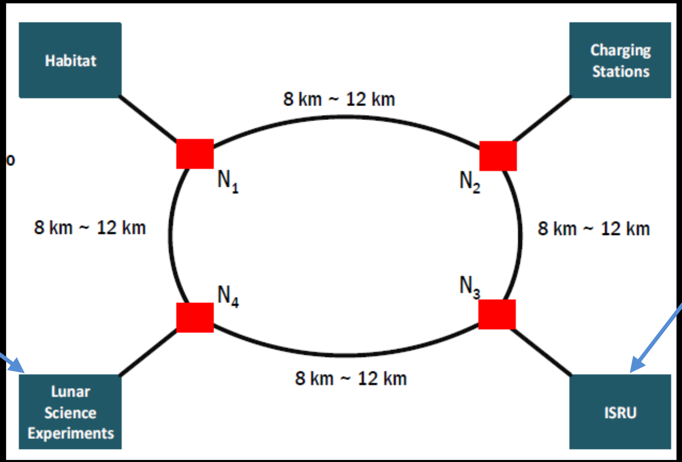
Flexible DC-Energy Router based on Energy Storage & Integrated Circuit Breaker
Ohio State University/Raytheon
NASA LuSTR Grant (academia-led)

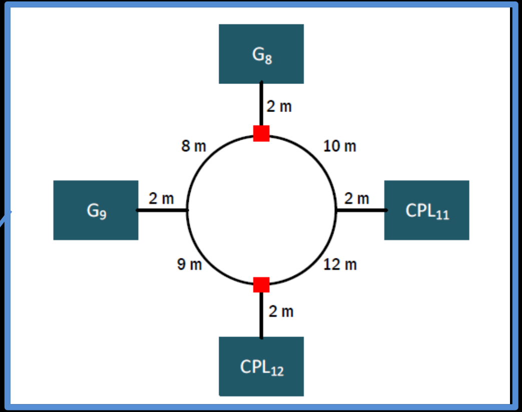


Wide bandwidth controller for grid resiliency

- Resiliency analysis based on graph theory
- Forecast-based energy management system for coordination and dispatching of power
- "Smart resistor" and batteries-in-loop to damp out instabilities
- Voltage/current sensors for fault detection
- Assume up to ~12 km transmission distance







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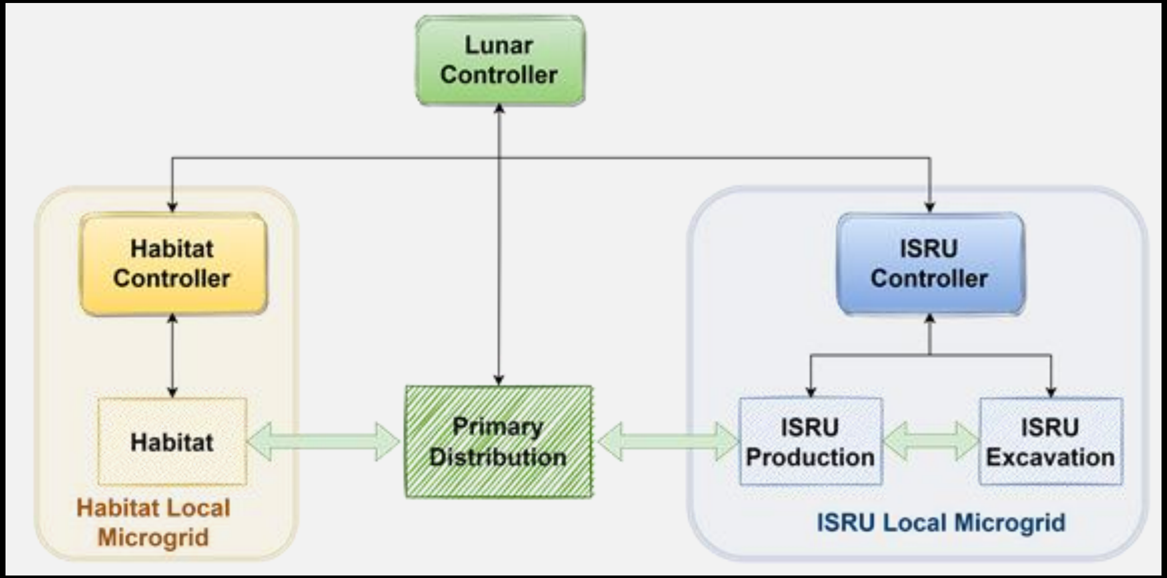
Technology for Lunar Surface Power – Current Projects

Power Management, Distribution, and Control *(cont'd)*

Autonomous Grid Controller
Autonomous Power Control for the Lunar Surface
NASA in-house, with DoE Sandia and DoD ARL

Automate Power Management and Control functions
- Fault management



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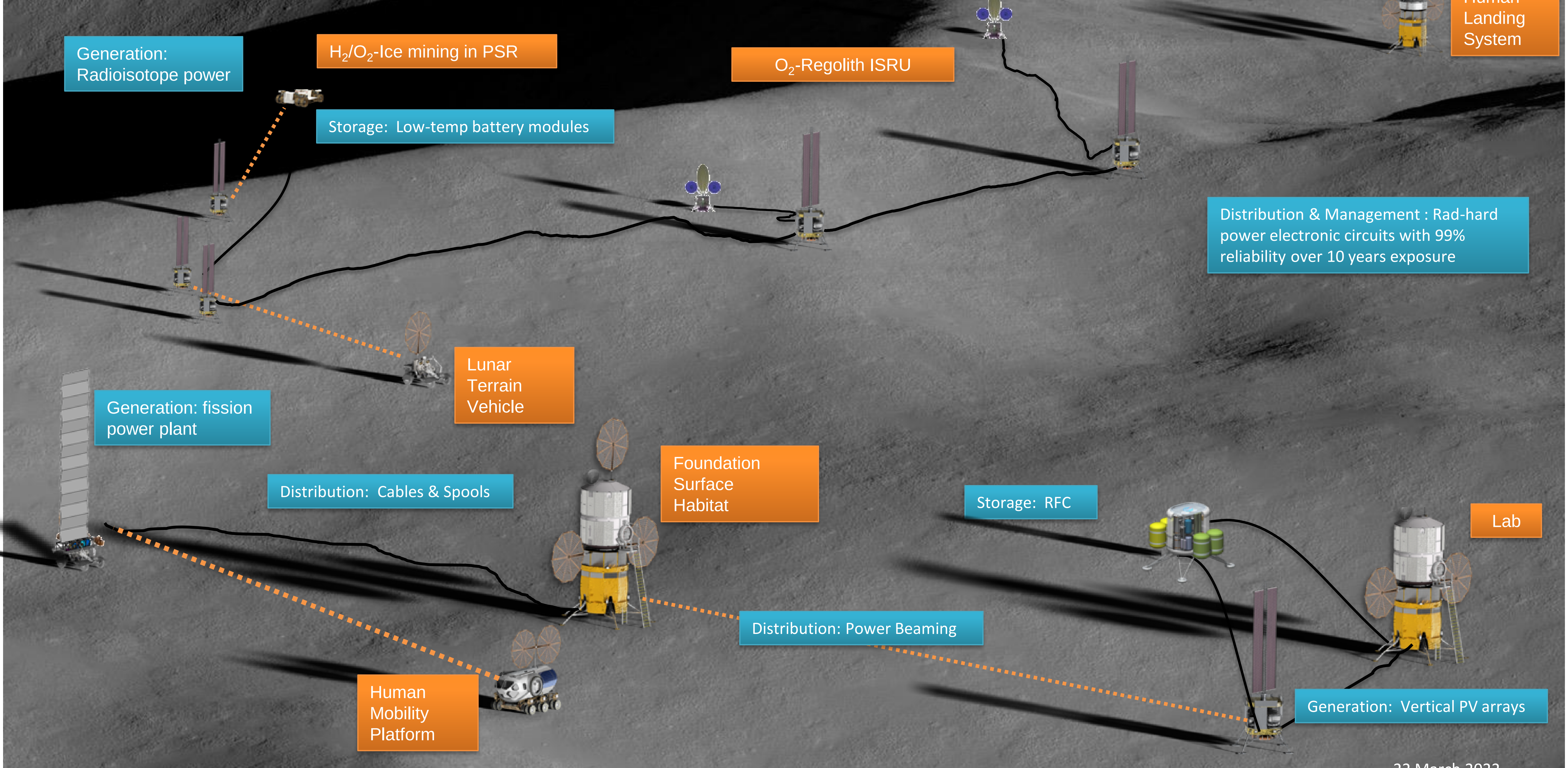
Building Block Power Technology Options for Initial Artemis South Pole “Outpost” (2030+)



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22 March 2022

ISRU Incremental Growth drives Power Demand Growth

Phases of Evolution and Use

Demonstrate, Build Confidence, Increase Production and Usage

	Demo Scale	Pilot Plant	Crewed Ascent Vehicle[1]	Full Descent Stage[1]	Lockheed Martin[6]		Dynetics[6] Single Stage/ Drop Tanks	Single Stage to NRHO[2]	Human Mars Transportation[3]	Commercial Cis-Lunar Transportation[4]
			3 Stage Arch to NRHO		2 Stage	Single Stage				
Timeframe	days to months	6 mo - 1 year	1 mission/yr	1 mission/yr	per mission	per mission	per mission	1 mission/yr	per year	per year
Demo/System Mass[5]	10's kg to low 100's kg	1 mt O_2 Pilot 1.3 – 2.5 mt Ice Mining	1400 to 2200 kg	2400 to 3700 kg				Not Defined	Not Defined	29,000 to 41,000 kg
Amount O_2	10's kg	1000 kg	4,000 to 6,000 kg	8,000 to 10,000 kg	10,000 kg	33,000 kg	32,000 kg	30,000 to 50,000 kg	185,000 to 267,000 kg	400,000 to 2,175,000 kg
Amount H_2	10's gms to kilograms	125 kg		1,400 to 1,900 kg	2,000 kg	7,000 kg	Methane Fuel	5,500 to 9,100 kg	23,000 to 33,000 kg	50,000 to 275,000 kg
Power for O_2 in NPS	100's W	5 to 6 KW	20 to 32 KW	40 to 55 KW				N/A	N/A	N/A
Power for H_2O in PSR	100's W	~2 KW		~25 KW				14 to 23 KW		150 to 800 KW
Power for H_2O to O_2/H_2 in NPS		~6 KW		~48 KWe				55 to 100 KWe		370 to 2,000 KWe

10 to 30 mT Range for
Initial Full-Scale Production

100 to 100 mT Range for
Commercial Production

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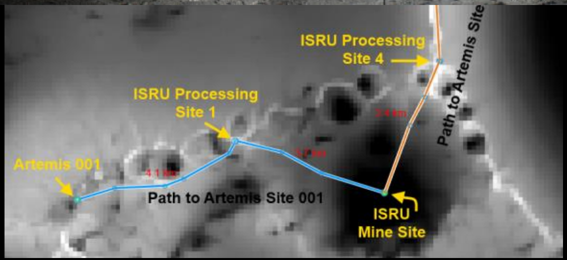
ISRU Products, Operations, and Resources Grow As Mission Needs and Infrastructure Grow

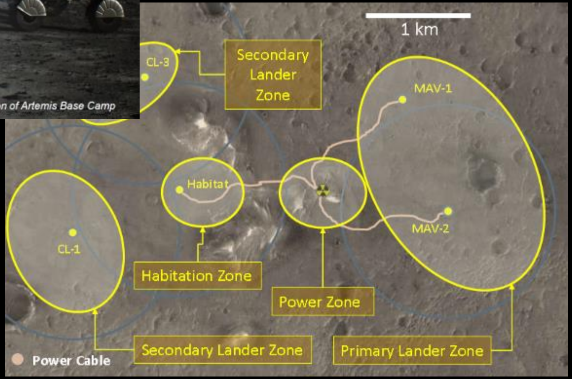
Initial Operations:

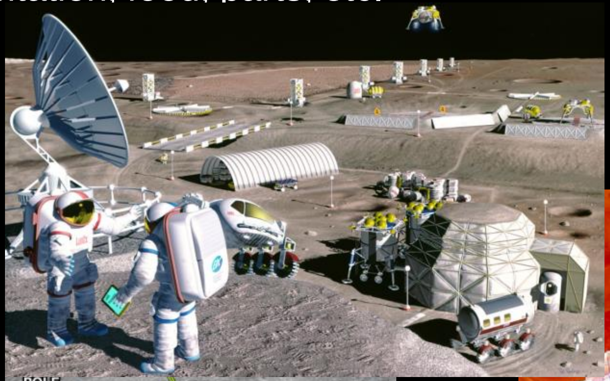
- Hardware delivered by multiple landers before crew arrives; Multiple landing zones
- Elements offloaded, moved, deployed, and connected together remotely
- Gaps of time between missions where crew is not present
- Each mission delivers extra hardware & logistics

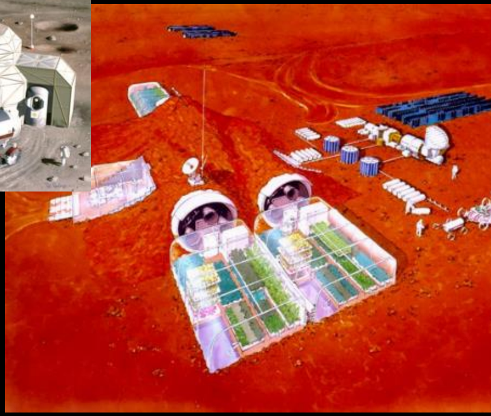
Ultimate Goal

- Consolidated and integrated infrastructure
- Indefinite stay with larger crews
- Roam (and mine) anywhere
- Earth independence; *In situ* ability to grow infrastructure: power, habitation, food, parts, etc.





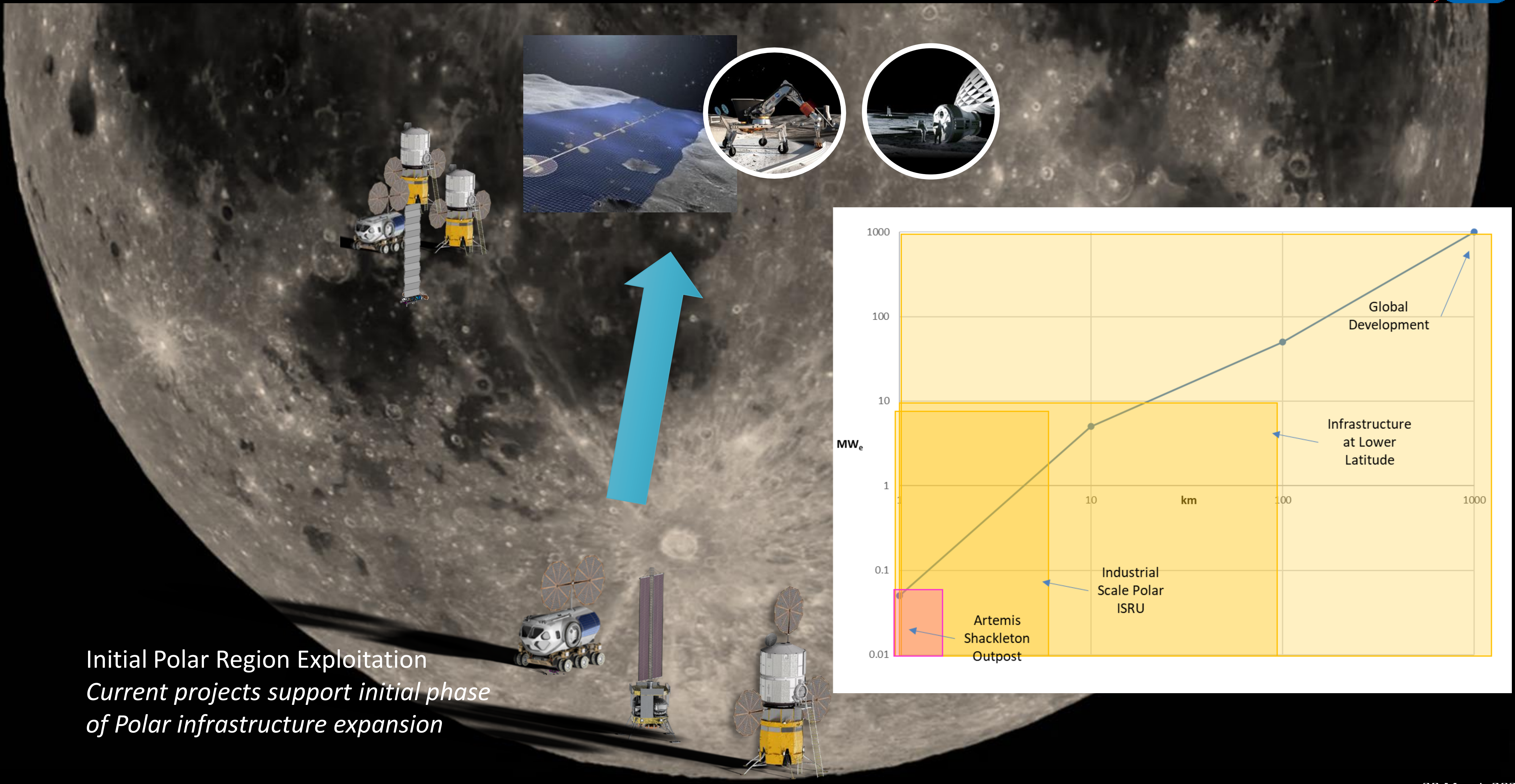




- **ISRU hardware integrated onto Landers or easily removed and assembled**
- **'Easy' Resource very close to landing site/ Ascent vehicle**

- **ISRU Plants consolidated with Product Storage**
- **Civil Engineering and *In Situ* Construction operations**
- **Resources can now be farther away from main base (ex. Deeper/larger PSRs)**
- **More/different resources needed for Earth independence**

Ultimate Global Exploitation



Initial Polar Region Exploitation

Current projects support initial phase of Polar infrastructure expansion

Polar Building Block Power Technologies Can Bootstrap Generation, Storage and Distribution at Lower Latitudes (2040+)

Generation: Vertical PV arrays

Storage: Low temperature battery modules

Distribution: Cables & Spools

Generation: Radioisotope power

Storage: RFC

Distribution: Power Beaming

- Landing pads and protective structures
- 100’s to 1000’s metric tons of regolith-based feedstock for construction projects
- 10’s to 100’s metric tons of metals, plastics and binders

Distribution: ISRU Aluminum cables

Generation: ISRU Silicon Photovoltaics

Generation: Fission power plant

Fission Power drives equipment to print photovoltaic generation, electrochemical, storage, and thermal storage from regolith

Human Landing System

Labs

Surface Habitats

Human Mobility Platforms

Lunar Terrain Vehicles

Lunar Surface Innovation Consortium (LSIC)

Nationwide alliance of universities, commercial companies, non-profit research institutions, NASA, and Other Government Agencies with a vested interest in our nation's campaign to establish a sustained presence on the Moon.

LSIC Objectives include:

- Identifying lunar surface technology needs and assessing the readiness of relative systems and components
- Making recommendations for a cohesive, executable strategy for development and deployment of the technologies required for successful lunar surface exploration
- Providing a central resource for gathering information, analytical integration of lunar surface technology demonstration interfaces, and sharing of results.

Focus Groups (FG) are the primary means for consistent interaction with the LSIC Community. This includes:

- Establishing collaborative relationships among members via virtual monthly forums, quarterly virtual workshops, and LSIC member site visits
- Building community and developing talent
- Compiling member input and reporting outcomes and recommendations

If interested in further information, please visit lsic.jhuapl.edu


www.nasa.gov/spacetech